International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2016 | Issue 26 | Volume 8 | Number 1 | Pages 36-44

OPTIMAL DESIGN OF FOPID CONTROLLER FOR LFC IN AN INTERCONNECTED MULTI-SOURCE POWER SYSTEM

H. Shayeghi A. Molaee A. Ghasemi

Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran
hshayeghi@gmail.com, amolaee.a@gmail.com, ghasemi.agm@gmail.com

Abstract- This paper addresses optimal design and performance analysis of the Social Spider Optimization (SSO) algorithm based Fractional Order Proportional Integral Derivative (FOPID) controller for load frequency control (LFC) in an interconnected multi-source power system. Since this controller has more adjusted parameters than classical proportional-integral-derivative (PID) controller, thus it provides better dynamics performance. Hereby, optimal tuning of controller parameters is converted to an optimization problem with time domain objective function which SSO algorithm solves it. The proposed objective function consists of frequency deviation in each area and tie-line power deviation which using appropriate weighting coefficients are associated with each other. The proposed controller has been applied on a two-area test system includes six generating units which one of them has (High Voltage Direct Current (HVDC) link. The simulation results show good performance in comparison with other well-known controller. Furthermore, to illustrate the robustness and stability of the proposed controller, the power system has been studied under nonlinearities conditions such as Generation Rate Constraint (GRC) and Governor Dead Band (GDB) and uncertainties in system parameters with changing between -50% to +50% of nominal values. The results show the high ability of the optimized FOPID controller based on SSO algorithm to overcome the LFC problem in multi-source two area interconnected power system.

Keywords: FOPID Controller, GRC, GDB, Multi-source Power System, SSO Algorithm.

I. INTRODUCTION

LFC is one of the most important issues in design of a suitable controller for the interconnected power systems. The main purpose of the LFC problem is to hold the frequency and exchanged tie-line power deviations at the acceptable limits under different load demands and operating conditions which it can be done by good adjusting of units output. Since, the frequency deviation affects on the reliability of the system, therefore, damp of transient deviations in each control area is very necessary to done quickly [1].

Hence, many researchers over the world have done many efforts to find suitable methods to hold the frequency in each area at or near its nominal value and restore it after occurrence a disturbance in the interconnected power system. Large-scale power system comprises of some interconnected subsystems along with power generation units and different nonlinearities that make it hard to control. Therefore, the appropriate scheme to control the power system should be adopted.

There are some literatures review on LFC studies [2, 3] that have discussed the different type of generating units and their effects on the power system stability. The intelligent controllers such as the fuzzy approach [4-6], the Artificial Neural Network (ANN) [7], the adaptive Neuro-fuzzy Interference System (ANFIS) [8], proportional-integral (PI) and Proportional-Integral-Derivative (PID) controller [9], self-tuning fuzzy type PID controllers [10] are used to LFC design in an interconnected power system. The integer order (IO) type controller such as PI and PID has the simplicity in designing and implementation to maintain the frequency at the specified value in the interconnected power system, but subjected to wide variation in the load disturbance, don't have the good dynamics performance.

To overcome these problems, fractional order based controller is used. The better performance of the Fractional Order Proportional Integral Derivative controller in comparison with IO type controller is shown for multi-area AGC problem under deregulated environment [11]. Main advantage of the FOPID controller is two extra parameters known as λ (non-integer order of integrator) and μ (non-integer order of differentiator) in the controller structure that provide two more degrees of freedom in controller design. The FOPID controllers are used in the various fields of engineering.

The FOPID controller is used in [12-14] for automatic voltage regulator system, in [15] for state-space self-tuning control, in [16] for weapon system, in [17] for tuning of the FOPID controller using a regression model with a fractional order time delay system. The main problem of LFC is not only designing of a stable controller but also finding the optimal control parameters in order to the interconnected power system has a good performance in various loading and operation points.

Hence, the different intelligent optimization methods such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) that are available in [18-21] have been applied to LFC problem. In this paper, the SSO based FOPID controller is proposed to solve the LFC problem in multi-source two area interconnected power system with three power generation units in each area comprises of thermal, hydro and gas units. Because, the SSO algorithm has a high ability to balance between the exploitation the solutions are found so far and exploration of search space, furthermore to overcome the premature convergence, it is used to find the optimal controller parameters.

The implementation results of the SSO based FOPID controller is compared with the results of tuned PID controller based on Teaching Learning Based Optimization (TLBO) method and the superiority of SSO based FOPID has shown. For showing the good performance of this method to control the multi-source power system, the nonlinearities such as GRC and GDB and uncertainties in the power system parameters are considered in the studies. The simulation results show the good performance and high capability of the proposed controller in presence of power system uncertainties and nonlinearities in comparison with another method.

II. OVERVIEW ON FRACTIONAL CALCULUS

Various definitions for fractional order calculus such as Grunwald-Letnikov (GL), Riemann-Liouville (RL) and Caputo's statements have been reported in the literature [23-25] and one of them is selected here. In this paper, Caputo's definition is chosen that is as follows:

$${}_{\alpha}D_t^{\beta} f(t) = \frac{1}{\Gamma(\beta - m)} \int_{\alpha}^{t} \frac{f^{(m)(\tau)}}{(t-\tau)^{\beta - m + 1}} d\tau \tag{1}$$

where the details are available in [26].

In order to implement the fractional order operator in practical studies, it has to be approximated with integer order transfer functions. There are several approximations such as Oustaloup's approximation [27] that can be applied. In this paper, this approximation method is used. The transfer function of differentiator operator (s^{β}) according to the Oustaloup's approximation is as follows:

$$s^{\beta} = I \prod_{i=-P}^{P} \frac{s + \omega_i'}{s + \omega_i} \tag{2}$$

where the zeros, poles and gain for a positive β can be obtained from follows equations within the frequency range [ω_l, ω_h], respectively as:

$$\omega_i' = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{\frac{i+P+0.5(1-\beta)}{2P+1}} \tag{3}$$

$$\omega_i = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{\frac{i+P+0.5(1+\beta)}{2P+1}} \tag{4}$$

$$I = \left(\frac{\omega_h}{\omega_l}\right)^{-\frac{\beta}{2}} \prod_{i=-P}^{P} \frac{\omega_i}{\omega_i'} \tag{5}$$

Similar formulations can be achieved for $\mu<0$ with this difference that the role of zeros and poles is exchanged. In the simulations for an approximation of fractional operators, high-frequency limit (ω_h) is 1000, low-frequency limit (ω_l) is 0.001 and P=5.

III. SOCIAL SPIDER ALGORITHM

Social Spider algorithm is a swarm-based algorithm that proposed by Erik Cuevas et al in 2013 [22]. This algorithm simulates the collective behavior of social spiders and acts according to the two different search operators are known as females and males. Some optimization algorithms such as PSO and ABC have the major defect in premature convergence and hardship to overcome the local optimum (exploration-exploitation balance). The SSO algorithm because of its special structure has been able to solve these problems, therefore, it is selected to solve the LFC problem in this paper.

The structure, mathematical Configuration and biological details related to the SSO are available in [22] and here the summary is described. The SSO algorithm is produced using biological behavior in social spider colony. It is assumed that all spiders are communicating with each other on the common web as search space.

The spiders' communication is performed using production the vibrations by themselves to transmit the information. These vibrations are different based on weight and distance of the spider that produces them. In this algorithm, there are three different types of vibrations as following:

Vibci is the perceived vibrations by member $i(s_i)$ related to the nearest member $b(s_c)$ to the member i that $w_c>w_i$. *Vibbi* is the perceived vibrations by member $i(s_i)$ related to the heaviest member $c(s_b)$ in the whole population. *Vibfi* is the perceived vibrations by member $i(s_i)$ related to the nearest member (female) $f(s_f)$ to the member *i*.

One of the interesting characteristics of social spiders is that the population of female spiders N_f is more than the male spiders N_m. For starting the algorithm, female spiders are randomly selected between 0.6%-0.9% of the whole population N. In Figure 1, the flow chart of SSO algorithm is drawn and its details are available in [22].

IV. DESIGN OF FOPID USING SSO FOR LFC

A. FOPID Controller

Certainly, the Proportional-Integral-Derivative controllers are yet the most applicable controllers among other types for industrial applications [28]. In [29] this controller has been generalized using conversion the integer order of differentiator and integrator into the fractional order and known as fractional order PID controller. The difference between the conventional PID and fractional order PID (PIλDμ) is the two extra parameters in the FOPID controller (non-integer order of differentiator and integrator) that makes more flexibility in controller design and improves the system dynamics response. Mathematical formulation of FOPID controller is as follows:

$$C(s) = K_P + K_I \frac{1}{S^{\lambda}} + K_D S^{\mu} \tag{6}$$

where, K_P, K_I and K_D are the proportional, integrator and derivative coefficient, also λ and μ are the fractional order of integrator and fractional order of differentiator, respectively. The following will be shown this controller has the better performance in comparison with the integer order PID controller.

B. Power System Modelling

In this paper, the system under study is a multi-source two area interconnected power system includes six generation units contains reheat thermal, Hydro and gas unit in each control area (Figure 2). To achieve the reliable and safety operation of power system, it's necessary that one controller has been considered for each generation unit. Each power plant consists of the speed governing system, turbine and generator that for simplicity at analysis in the frequency domain, the transfer functions are used for modelling the power system components.

The under study power system parameters in Figure 2 and transfer functions are defined in [30] and value of them are available in Appendix. There are three inputs and two outputs in the under study system. The load disturbances ΔP_D, controller input U and Tie-line power deviation $\Delta P_{Tie\text{-}line}$ are the inputs. The frequency deviation of each control area Δf and Area Control Error (*ACE*) are the outputs.

The *ACE* enters the controller and for each control area is defined as following:

$$ACE_i = B_i \Delta f_i + \Delta P_{Tie-line} \tag{7}$$

C. Tuning the FOPID Using SSO

In this paper, an FOPID controller has been considered for each power generation unit and an FOPID controller has five parameters for tuning using SSO algorithm. To illustrate the better performance of the SSO based FOPID controller, it has been compared with TLBO based PID controller [30]. The FOPID Controller is applied on the two area multi-source interconnected power system includes six generating units comprises thermal, hydraulic and gas units, once considering HVDC link and regardless of it.

For optimal tuning of control parameters using SSO algorithm, it is necessary to definite the appropriate objective function. In this paper, the proposed objective function formulation is given by:

$$\begin{aligned} J &= a_1 ISE + a_2 ITSE + a_3 IAE + a_4 ITAE + \\ &+ a_5 ISTSE + a_6 ISTAE + a_7 T_s \end{aligned} \tag{8}$$

The above terms in Equation (8), are the sum of the settling time (ST_i) of frequency deviation of each control area and tie-line power deviation and some error criteria such as Integral of Squared Error (*ISE*), Integral of Time multiplied Squared Error (*ITSE*), Integral of Absolute Error (*IAE*), Integral of Time multiplied Absolute Error (*ITAE*), Integral Square Time of Square Error (*ISTSE*) and Integral Square Time of Absolute Error (*ISTAE*). The proper coefficients (a_i) have multiplied in error criteria in order to the effective values of theme in summation will be in the same range.

$$ISE = \int_o^{tsim} \left(\sum_{i=1}^{n} (\Delta f_i)^2 + \sum (\Delta P_{Tie-line})^2\right) dt \tag{9}$$

$$ITSE = \int_o^{tsim} \left(\sum_{i=1}^{n} (\Delta f_i)^2 + \sum (\Delta P_{Tie-line})^2\right) t\,dt \tag{10}$$

$$IAE = \int_o^{tsim} \left(\sum_{i=1}^{n} |\Delta f_i| + \sum |\Delta P_{Tie-line}|\right) dt \tag{11}$$

$$ITAE = \int_o^{tsim} \left(\sum_{i=1}^{n} |\Delta f_i| + \sum |\Delta P_{Tie-line}|\right) t\,dt \tag{12}$$

$$ISTSE = \int_o^{tsim} \left(\sum_{i=1}^{n} (\Delta f_i)^2 + \sum (\Delta P_{Tie-line})^2\right) t^2 dt \tag{13}$$

$$ISTAE = \int_o^{tsim} \left(\sum_{i=1}^{n} |\Delta f_i| + \sum |\Delta P_{Tie-line}|\right) t^2 dt \tag{14}$$

$$T_s = \sum_{i=1}^{n} ST_i \tag{15}$$

where, Δf_i and $\Delta P_{Tie\text{-}line}$ are the frequency deviation in control area i and power exchange between each two control area in an interconnected power system, respectively.

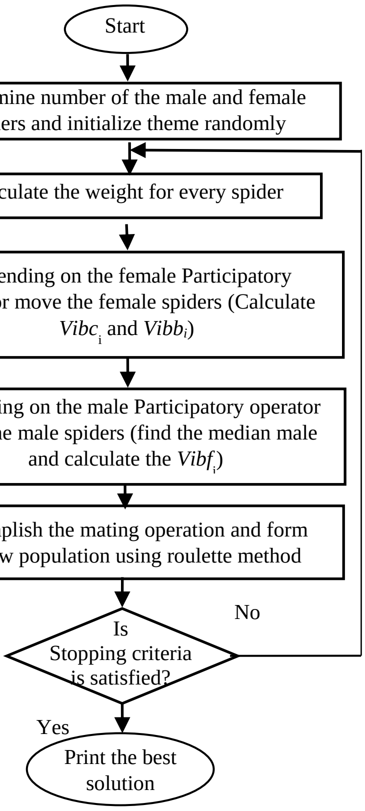


Figure 1. Flowchart of SSO algorithm

To tune the FOPID parameters, optimization problem is considered as minimizing the objective function. The control parameters boundaries are as follows:

$$\begin{gathered} K_P^{\min} < K_P < K_P^{\max}, K_I^{\min} < K_I < K_I^{\max}, K_D^{\min} < K_D < K_D^{\max} \\ \lambda^{\min} < \lambda < \lambda^{\max}, \mu^{\min} < \mu < \mu^{\max} \end{gathered} \tag{16}$$

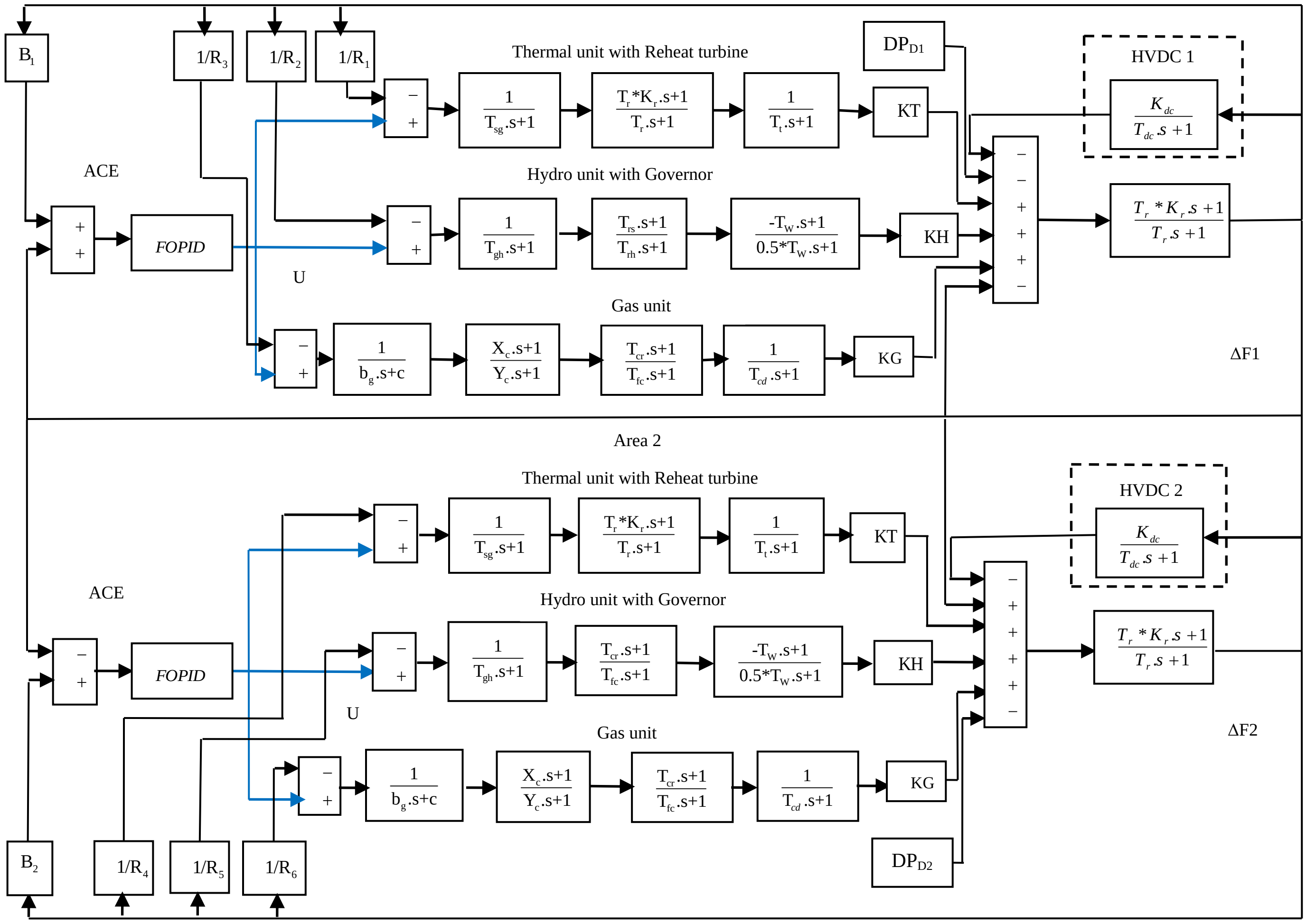
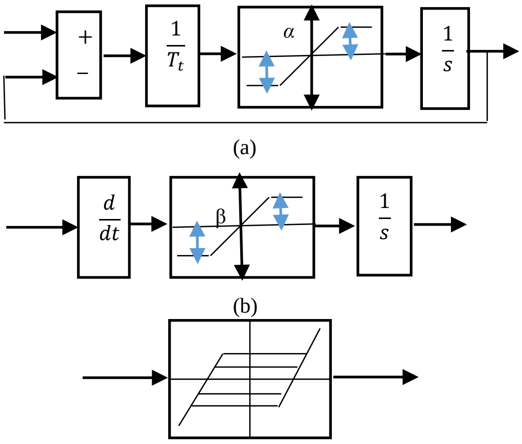


Figure 2. Multi-source two area interconnected power system



(a)

(b)

(c)

Figure 3. The GRC model for the (a) thermal unit, (b) Hydro unit and (c) the GDB model for both unit

The change range of K_P, K_I and K_D for optimization implementation are selected in (0, 10) and the λ and μ are optimized in (0, 2). The parameters of the SSO algorithm to apply on LFC problem are available in Table 1. At first, Simulation is performed in presence of AC lines only and then is performed in presences of both of AC lines and HVDC link (Figure 2).

Frequency deviations of control areas and tie-line power deviations for 1% step load disturbance in area 1 using the proposed objective function are shown in Figures 4-9. Values of some error criteria such as *ISE*, *ITSE*, *IAE*, *ISAE*, *ISTSE*, *ISTAE* and settling time of frequency deviations of control areas and tie-line power deviations are compared with same obtained results by the PID based on TLBO and given in Tables 2 and 3. The FOPID controller parameters tuned using the SSO algorithm are available in Table 4. According to the comparisons, it can be found that the SSO based FOPID controller proposed in this paper has the better performance than the TLBO based PID controller adopted from [30].

By looking at the settling time and domain of frequency deviations of control areas and tie-line power deviations, it can be seen that in most cases the FOPID controller has a better performance in comparison with PID Type at the damping of the frequency and tie-line power deviations. Also, results of the implementation of the FOPID controller to the multi-source two-area power system show ability of the proposed control method in solve the LFC problem. The given data in the Tables 2 and 3 prove these statements, because the values of settling time and error criteria are reduced in all cases in comparison with obtained results from TLBO based PID controller adopted from [30].

Table 1. Value of SSO algorithm parameters for LFC problem

Parameters	Value
Population size	100
Iteration	100
Female Percent	88
Male percent	12
Upper limit of K_p, K_I and K_D	+10
Lower limit of K_p, K_I and K_D	0
Upper limit of λ and μ	2
Lower limit of λ and μ	0

Table 2. Value of error criteria and settling time in proposed objective function with AC tie-line only

Criteria	FOPID (SSO)	PID (TLBO)
ISE	5.2803×10^{-05}	11.1210×10^{-02}
ITSE	2.4243×10^{-05}	15.4289×10^{-04}
IAE	1.2500×10^{-02}	11.3410×10^{-02}
ITAE	1.1500×10^{-02}	30.1024×10^{-04}
ISTSE	1.9222×10^{-05}	
ISTAE	4.5500×10^{-02}	
Settling Time (0.2%)		
Δf_1	3.5524	6.9716
Δf_2	3.2128	18.5284
$\Delta P_{Tie\text{-}line}$	5.4463	14.3129

Table 3. Value of error criteria and settling time in proposed objective function with AC-DC lines

Criteria	FOPID (SSO)	PID (TLBO)
ISE	2.8296×10^{-05}	3.438842×10^{-05}
ITSE	1.0647×10^{-05}	2.197295×10^{-05}
IAE	9.0000×10^{-03}	0.0163
ITAE	1.1400×10^{-02}	0.10296
ISTSE	1.0018×10^{-05}	
ISTAE	3.6200×10^{-02}	
Settling Time (0.2%)		
Δf_1	2.4852	5.5616
Δf_2	6.0992	9.3024
$\Delta P_{Tie\text{-}line}$	4.5994	12.8285

Table 4. Value of tuned FOPID controller parameters using SSO algorithm

		Control Parameters	Thermal	Hydro	Gas
Model without HVDC	Area 1	K_p	5.2787	5.4910	5.9314
		K_I	8.4939	6.4678	8.1081
		K_D	9.0376	3.6442	2.8052
		λ	0.6617	0.8305	0.8960
		μ	0.8179	0.7581	0.1932
	Area 2	K_p	6.8944	4.9457	2.3513
		K_I	8.3921	2.7146	7.5044
		K_D	1.1769	0.9020	9.5766
		λ	0.3682	0.9076	1.0887
		μ	1.3886	1.3529	1.3347
Model with HVDC	Area 1	K_p	9.5563	5.2768	7.5201
		K_I	9.9131	7.0387	1.9160
		K_D	2.3558	3.9756	6.2554
		λ	0.7647	0.4316	0.9197
		μ	1.3742	0.5693	1.3244
	Area 2	K_p	3.5318	4.8435	2.9289
		K_I	3.4432	3.8118	6.1112
		K_D	4.2847	2.9912	1.0020
		λ	1.3033	0.6936	0.2891
		μ	0.2424	0.4118	1.4795

To demonstrate the robustness of suggested control method in the presence of the uncertainties and nonlinearities in the power system, the SSO based FOPID controller has been applied on the multi-source two area interconnected power system considering the change of the T_t, T_w, T_{cd} and T_{sp} from their nominal values in range of ±50%.

Furthermore, the GRC and GDB in the Thermal and Hydro units are considered. The power generation of the thermal and Hydro units can change at the specified maximum range that called GRC. The GDB is described as a continuous change in the governor speed until there is no change in valve position. GDB makes the more oscillation in the power system frequency and exchanged tie-line power while the perturbation occurs in the power system. In this paper, the 3%/min for the thermal unit (α) and 270%/min for raising generation and 360%/min for lowering generation for hydro unit (β) is selected as GRC.

Also, the value of GDB is 0.06% [31]. The used GRC and GDB models are shown in the Figure 3. The frequency and tie-line power deviation are shown in Figures 10-12. The related values to the error criteria, settling time, maximum overshoot and rise time of frequency and tie-line power deviation that are given in the Table 5, illustrate high capability of the proposed control technique in keeping the power system stability and reliability in the presence of wide range changes of power system parameters.

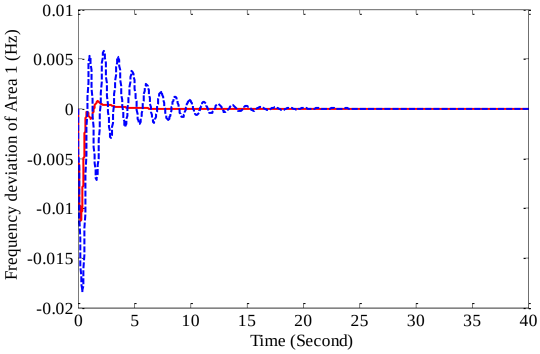


Figure 4. Frequency deviations of area 1 for 1% step load disturbance in area 1 without HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

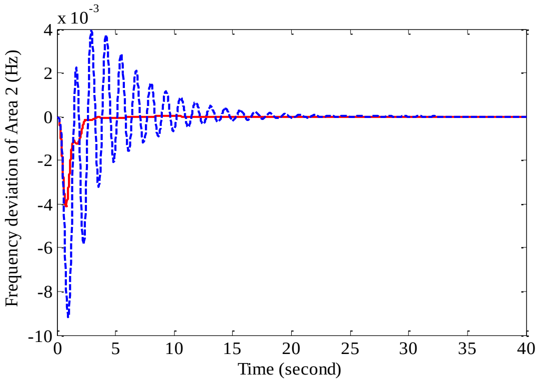


Figure 5. Frequency deviations of area 1 for 1% step load disturbance in area 1 without HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

The settling time of frequency deviation of area 1 without HVDC link for PID-TLBO is 56.9716 s and for FOPID- SSO controller is 3.5524 s, same time for frequency deviation of area 2 is 9.3024 s for PID-TLBO and is 6.0992 s and for tie-line power deviation is 14.3129 s for PID-TLBO and is 5.4463 s for FOPID-SSO. It can be seen the performance of FOPID controller based on SSO algorithm in all cases is better than the PID controller based on TLBO algorithm. If same analysis is performed for other criteria that are given in Tables 2 and 3, this superiority will reveal.

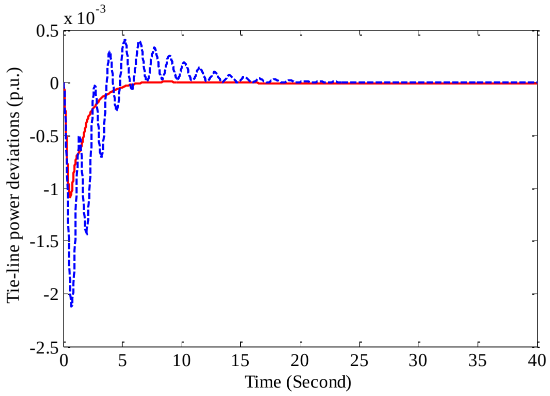


Figure 6. Tie-line power deviations for 1% step load disturbance in area 1 without HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

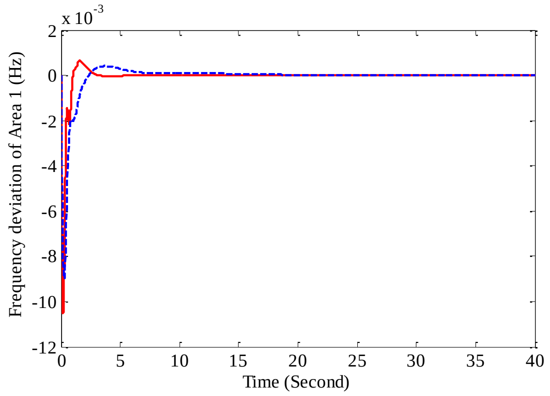


Figure 7. Frequency deviations of area 1 for 1% step load disturbance in area 1 with HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

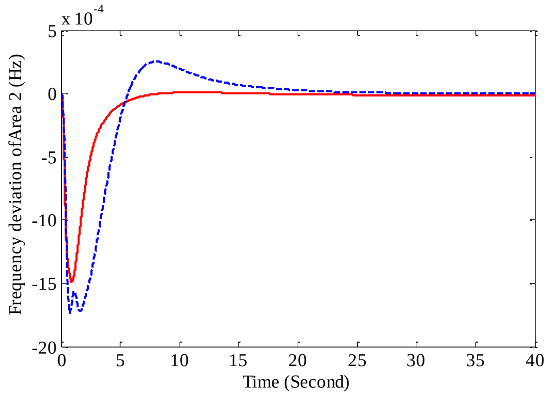


Figure 8. Frequency deviations of area 2 for 1% step load disturbance in area 1 with HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

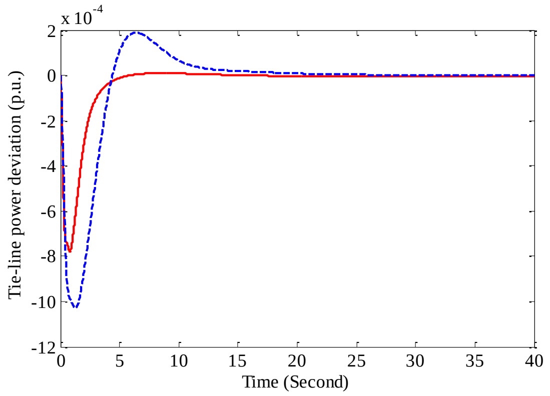


Figure 9. Tie-line power deviations for 1% step load disturbance in area 1 with HVDC; Solid (FOPID-SSO) and dashed (PID-TLBO)

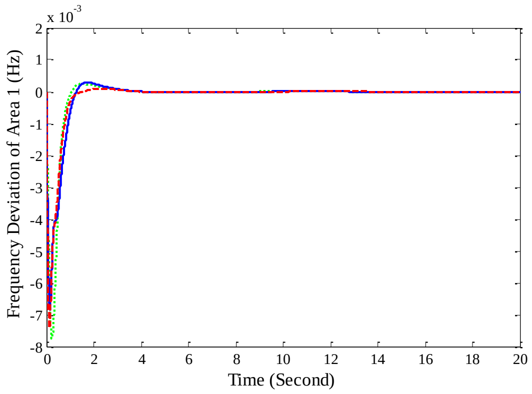


Figure 10. Frequency deviations of area 1 for 1% step load disturbance in area 1 with HVDC, Dashed (-50% of nominal value), Solid (nominal value) and dotted (+50% of nominal value)

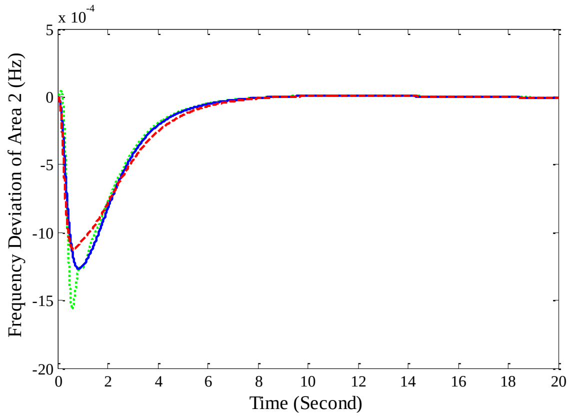


Figure 11. Frequency deviations of area 2 for 1% step load disturbance in area 1 with HVDC, dashed (-50% of nominal value), Solid (nominal value) and dotted (+50% of nominal value)

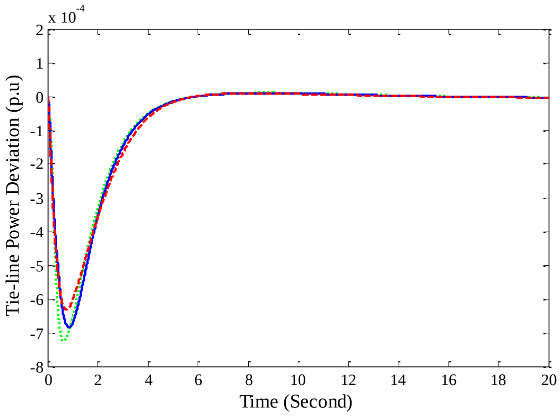


Figure 12. Frequency deviations of area 1 for 1% step load disturbance in area 1 with HVDC, Dashed (-50% of nominal value), Solid (nominal value) and dotted (+50% of nominal value)

According to the obtained results of table 5 and Figures 10-12, the value of error criteria, settling time, rise time and overshoot for frequency deviations of each control area and tie-line power deviation have a little difference. For example, the values of settling time, rise time and overshoot of frequency deviation of area 1 are 1.1394 s, 0.0001 s and 0.0106, respectively for -50% change in power system parameters. These values for nominal parameters are 2.4852 s, 0.0002 s and 0.0663 and for +50% change in power system parameters are 2.4321 s, 0.0002 s and 0.0255.

With comparison of these values can be observed the stability of proposed controller against various uncertainties. These outcomes illustrate that the FOPID controller based on SSO algorithm has a high ability in improvement the dynamics performance of the multi-source two area interconnected power system in presence of various operation conditions and some nonlinearities such as GRC and GDB and uncertainties in the power system parameters.

Table 5. Value of error criteria, settling time, rise time and maximum overshoot in presence of ±50% change at system parameters

Parameters Change	-50%	Nominal Value	+50%
ISE	1.6688×10^{-05}	1.7319×10^{-05}	2.1520×10^{-05}
ITSE	7.8390×10^{-05}	0.9027×10^{-05}	9.6685×10^{-05}
IAE	0.0086	0.0091	2.1520×10^{-05}
ITAE	0.0329	0.0326	0.0309
ISTSE	1.8166×10^{-05}	1.8354×10^{-05}	1.6758×10^{-05}
ISTAE	0.6973	0.6833	0.6519
Δf_1			
Settling Time (0.2%)	1.1394	2.4852	2.4321
Rise Time	0.0001	0.0002	0.0002
Overshoot	0.0106	0.0663	0.0255
Δf_2			
Settling Time (0.2%)	6.8780	6.0992	6.1653
Rise Time	0.0318	0.0365	0.0064
Overshoot	0.0022	0.0022	0.0053
$\Delta P_{Tie\text{-}line}$			
Settling Time (0.2%)	10.3924	4.5994	10.5514
Rise Time	0.0143	0.0159	0.0183
Overshoot	0.0015	0.0015	0.0016

V. CONCLUSION

In this paper, the SSO based FOPID controller is proposed for solve the LFC problem in a multi-source two area interconnected power system. The investigated objective function is combination of some error criteria consist of *IAE*, *ITAE*, *ISTAE*, *ISE*, *ITSE*, *ISTSE* and settling time of the frequency deviations of control areas and tie-line power deviations. The control parameters has been tuned using SSO algorithm that is capable at obtaining the optimum solutions in optimization problems. The simulation results show that the SSO based FOPID controller has a higher ability than the TLBO based PID method in damping the frequency deviation of control areas and tie-line power deviation. Furthermore, the proposed control method has been applied to the same case study considering some nonlinearities such as GRC and GDB and parameters uncertainties in power system. The results reveal high ability of the proposed control method at balancing the power system frequency deviations in presence of uncertainties, nonlinearity in power system structure and load disturbance.

APPENDIX

The value of under study system parameters in Figures 2 are given below:

f = 60 Hz; $B_1 = B_2$ = 0.4312 pu MW/Hz; PR = 2000 MW (rating), PL = 1840 MW (nominal loading); $T_{r1} = T_{r2}$ = 10 s; $K_{r1} = K_{r2}$ = 0.3; $T_{t1} = T_{t2}$ = 0.3 s; $R_1 = R_2 = R_3 = R_4 = R_5 = R_6$ = 2.4 Hz/pu MW; $T_{sg1} = T_{sg2}$ = 0.08 s; $K_{T1} = K_{T2}$ = 0.543478; $K_{H1} = K_{H2}$ = 0.326084; $K_{G1} = K_{G2}$ = 0.130438; $T_{gh1} = T_{gh2}$ = 0.2 s; $T_{\mathrm{rh}1} = T_{rh2}$ = 28.75 s; $T_{rs1} = T_{rs2}$ = 5 s; $T_{W1} = T_{W2}$ = 1 s; $b_{g1} = b_{g2}$ = 0.5; c_g = 1; X_c = 0.6 s; $Y_{c1} = Y_{c2}$ = 1 s; $T_{cr1} = T_{cr2}$ = 0.01 s; $T_{fc1} = T_{fc2}$=0.23 s; $T_{cd1} = T_{cd2}$ = 0.2 s; $T_{ps1} = T_{ps2}$ = 11.49 s; $K_{ps1} = K_{ps2}$ = 68.9566 Hz/pu MW; $T_{dc1} = T_{dc2}$ = 0.2 s; $K_{dc1} = K_{dc2}$ = 1; T_{12} = 0.0433 pu.

REFERENCES

[1] K. Parmar, S. Majhi, D. Kothari, "Load Frequency Control of a Realistic Power System with Multi-Source Power Generation", International Journal of Electrical Power & Energy Systems, Vol. 42, No. 1, pp. 426-433, 2012.

[2] H. Shayeghi, H. Shayanfar, A. Jalili, "Load Frequency Control Strategies: A State-of-the-Art Survey for the Researcher", Energy Conversion and Management, Vol. 50, No. 2, pp. 344-353, 2008.

[3] S.K. Pandey, S.R. Mohanty, N. Kishor, "A Literature Survey on Load-Frequency Control for Conventional and Distribution Generation Power Systems", Renewable and Sustainable Energy Reviews, Vol. 25, pp. 318-334, 2013.

[4] K. Bipirayeh, O. Abedinia, H. Shayanfar, "Optimal Multi-Stage Fuzzy PID Bundled PSOTVAC in Multimachine Environment", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 14, Vol. 5, No. 1, pp. 37-43, March 2013.

[5] S. Ghoshal, "Optimizations of PID Gains by Particle Swarm Optimizations in Fuzzy Based Automatic Generation Control", Electric Power Systems Research, Vol. 72, No. 3, pp. 203-212, 2004.

[6] H.A. Shayanfar, H. Shayeghi, A. Jalili, "Takagi-Sugeno Fuzzy Parallel Distribution Compensation Based Three-Area LFC Design", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 55-64, September 2011.

[7] H. Shayeghi, H.A. Shayanfar, "Application of ANN Technique Based on μ-Synthesis to Load Frequency Control of Interconnected Power System", International Journal of Electrical Power & Energy Systems, Vol. 28, No. 7, pp. 503-511, 2006.

[8] H. Shayeghi, H.A. Shayanfar, "PSO Based Neuro-Fuzzy Controller for LFC Design Including Communication Time Delays", International Journal of Electrical Power & Energy Systems, Vol. 2, No. 2, pp. 28-36, 2010.

[9] E. Cam, I. Kocaarslan, "A Fuzzy Gain Scheduling PI Controller Application for an Interconnected Electrical Power System", Electric Power Systems Research, Vol. 73, No. 3, pp. 267-274, 2005.

[10] E. Yesil, M. Guzelkaya, I. Eksin, "Self-Tuning Fuzzy PID Type Load and Frequency Controller", Energy Conversion and Management, Vol. 45, No. 3, pp. 377-390, 2004.

[11] S. Debbarma, L. Saikia, N. Sinha, "AGC of a Multi-Area Thermal System under Deregulated Environment

Using a Non-Integer Controller", Electric Power Systems Research, Vol. 95, pp. 175-183, 2013.

[12] M. Zamani, M. Karimi Ghartemani, N. Sadati, M. Parniani, "Design of a Fractional Order PID Controller for an AVR Using Particle Swarm Optimization", Control Engineering Practice, Vol. 17, No. 12, pp. 1380-1387, 2009.

[13] Y. Tang, M. Cui, C. Hua, L. Li, Y. Yang, "Optimum Design of Fractional Order $PI^{\lambda}D^{\mu}$ Controller for AVR System Using Chaotic ant Swarm", Expert Systems with Applications, Vol. 39, No. 8, pp. 6887-6896, 2012.

[14] I. Pan, S. Das, "Chaotic Multi-Objective Optimization Based Design of Fractional Order $PI^{\lambda}D^{\mu}$ Controller in AVR System", International Journal of Electrical Power & Energy Systems, Vol. 43, No. 1, pp. 393-407, 2012.

[15] J. Tsai, T. Chien, S. Guo, Y. Chang, L. Shieh, "State-Space Self-Tuning Control for Stochastic Fractional-Order Chaotic Systems", IEEE Trans. Circuits Syst. I, Vol. 54, No. 3, pp. 632-642, 2007.

[16] L. Jia, M. Xiuyun, L. Zaozhen, "Freestyle Fractional Order Controller Design with PSO for Weapon System", Energy Procedia, Vol. 13, pp. 7577-7582, 2011.

[17] S. Agnihotri, L. Waghmare, "Regression Model for Tuning the PID Controller with Fractional Order Time Delay System", Ain Shams Engineering Journal, Vol. 5, No. 4, pp. 1071-1081, 2014.

[18] S. Ghoshal, S. Goswami, "Application of GA Based Optimal Integral Gains in Fuzzy Based Active Power-Frequency Control of Non-Reheat and Reheat Thermal Generating Systems", Electric Power Systems Research, Vol. 67, No. 2, pp. 79-88, 2003.

[19] H. Shayeghi, A. Jalili, H.A. Shayanfar, "Multi-Stage Fuzzy Load Frequency Control Using PSO", Energy Conversion and Management, Vol. 49, No. 10, pp. 2570-2580, 2008.

[20] H. Gozde, M.C. Taplamacioglu, I. Kocaarslan, "Comparative Performance Analysis of Artificial Bee Colony Algorithm in Automatic Generation Control for Interconnected Reheat Thermal Power System", International Journal of Electrical Power & Energy Systems, Vol. 42, No. 1, pp. 167-178, 2012.

[21] H. Shayeghi, H.A. Shayanfar, A. Ghasemi, "Application of ABC Algorithm for Action Based Dispatch in the Restructured Power Systems", Int. J. Tech. Phys. Probl. Eng., Vol. 4, pp. 114-19, 2012.

[22] E. Cuevas, M. Cienfuegos, D. Zaldivar, M. Perez Cisneros, "A Swarm Optimization Algorithm Inspired in the Behavior of the Social-Spider", Expert Systems with Applications, Vol. 40, No. 16, pp. 6374-6384, 2011.

[23] R. Caponetto, G. Dongola, L. Fortuna, I. Petra, "Fractional Order Systems", Modeling and Control Applications, World Scientific Series on Nonlinear Science, Series A, Singapore: World Scientific Publishing Co. Pvt. Ltd, Vol. 72, 2010.

[24] H. Ramezanian, S. Balochian, "Optimal Design a Fractional-Order PID Controller Using Particle Swarm Optimization Algorithm", International Journal of Control and Automation, Vol. 6, No. 4, 2013.

[25] S. Das, "Functional Fractional Calculus", Springer, Berlin, 2008.

[26] A. Oustaloup, X. Moreau, M. Nouillant, "The CRONE Suspension", Control Engineering Practice, Vol. 4, No. 8, pp. 1101-1108, 1996.

[27] B. Mohanty, S. Panda, P. Hota, "Differential Evolution Algorithm Based Automatic Generation Control for Interconnected Power Systems with Non-Linearity", Alexandria Engineering Journal, Vol. 53, No. 3, pp. 537-552, 2014.

[28] K. Astrom, T. Hagglund, "Advanced PID Control", Research Triangle Park, ISA - The Instrumentation, Systems and Automation Society, NC, 2006.

[29] I. Podlubny, "Fractional-Order Systems and $PI^{\lambda}D^{\mu}$ Controllers", IEEE Transactions on Automatic Control, Vol. 44, No. 1, pp. 208-214, 1999.

[30] A. Barisal, "Comparative Performance Analysis of Teaching Learning Based Optimization for Automatic Load Frequency Control of Multi-Source Power Systems", International Journal of Electrical Power & Energy Systems, Vol. 66, pp. 67-77, 2015.

[31] G.C. Sekhar, et al., "Load Frequency Control of Power System under Deregulated Environment Using Optimal Firefly Algorithm", International Journal of Electrical Power & Energy Systems, Vol. 74, pp. 195-211, 2016.

BIOGRAPHIES

Hossein Shayeghi received the B.Sc. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is a full Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored and co-authored of 5 books in Electrical Engineering area all in Farsi, one book and two book chapters in international publishers and more than 325 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of three international journals. He has served on several other committees and panels in governmental, industrial, and technical conferences. He was selected as distinguished researcher of the University of Mohaghegh Ardabili several times. In 2007 and 2010, he was also elected as distinguished researcher in engineering field in Ardabil province of Iran. Furthermore, he has been included in the Thomson Reuters' list of the top one percent of most-cited technical Engineering scientists in 2015 and 2016, respectively. Also, he is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and senior member of IEEE.

Abdollah Molaee was born in Kermanshah, Iran, in 1988. He received the B.Sc. degree in Electrical Engineering from the Kermanshah University of Technology, Kermanshah, Iran, in 2013. He currently is M.Sc. degree student in Electrical Engineering at University of Mohaghegh Ardabili, Ardabil, Iran. His areas of interest in research are power system restructuring and application of heuristic optimization methods and robust control design to power system control.

Ali Ghasemi received the B.Sc. and M.Sc. (honors with first class) degree in Electrical Engineering from Isfahan University of Technology, Isfahan, and University of Mohaghegh Ardabili (UMA), Ardabil, Iran, in 2009 and 2011, respectively. Currently he is pursuing the Ph.D. degree in the Electrical Engineering and Computer Science of UMA. His research interests are application of forecast methods, operation adaptive and robust control of power systems, planning, power system restructuring and applications of heuristic techniques. He has authored of a book in electrical engineering area in Farsi, and more than 110 papers in reputable international journals and conference proceedings. Also, he collaborates as editorial committee and reviewer of 12 international journals. He is a member of the Iranian Association of Electrical and Electronic Engineers (IAEEE). In 2012 and 2013, he received the award of the 4th Electric Power Generation Conference and UMA for his M.Sc. thesis. He is the recipient honor M.Sc. and Ph.D. student award of UMA, 2014. He received the 2013 best young researcher award of the Young Researcher and Elite Club.